

STATUS OF EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY, AND THE FUTURE: GENIUS AND GENIUS-TF

H. V. KLAPDOR-KLEINGROTHAUS *

*Max-Planck-Institut für Kernphysik,
P.O. Box 10 39 80, D-69029 Heidelberg, Germany*

The first evidence for neutrinoless double beta decay has been observed in the HEIDELBERG-MOSCOW experiment, which is the most sensitive double beta decay experiment since ten years. This is the first evidence for lepton number violation and proves that the neutrino is a Majorana particle. It further shows that neutrino masses are degenerate. In addition it puts several stringent constraints on other physics beyond the Standard Model. The result from the HEIDELBERG-MOSCOW experiment is consistent with recent results from CMB investigations, with high energy cosmic rays, with the result from the g-2 experiment and with recent theoretical work. It is indirectly supported by the analysis of other Ge double beta experiments. The new project GENIUS will cover a wide range of the parameter space of predictions of SUSY for neutralinos as cold dark matter. Further it has the potential to be a real-time detector for low-energy (pp and ${}^7\text{Be}$) solar neutrinos. A GENIUS Test Facility has come into operation on May 5, 2003. This is the first time that this novel technique for extreme background reduction in search for rare decays is applied under the background conditions of an underground laboratory.

1. Introduction

In this paper we will describe in section II the recent evidence for neutrinoless double beta decay ($0\nu\beta\beta$), found by the HEIDELBERG-MOSCOW experiment^{1,2,3,4,5}, which is *since ten years now* the most sensitive double beta experiment worldwide.

This result is

$$T_{1/2}^{0\nu} = (0.8 - 18.3) \times 10^{25} \text{ y} \quad (95\%c.l.) \quad (1)$$

with best value of $T_{1/2}^{0\nu} = 1.5 \times 10^{25} \text{ y}$. Double beta decay is the slowest nuclear decay process observed until now in nature. Assuming the neutrino mass mechanism to dominate the decay amplitude, we can deduce

$$\langle m_\nu \rangle = (0.11 - 0.56) \text{ eV} \quad (95\%c.l.) \quad (2)$$

*Spokesman of HEIDELBERG-MOSCOW and GENIUS Collaborations,
E-mail: klapdor@gustav.mpi-hd.mpg, Home-page: http://www.mpi-hd.mpg.de.non_acc/

This value we obtain using the nuclear matrix element of ²². Allowing for an uncertainty of $\pm 50\%$ of the matrix elements (see ^{5,14}), this range widens to $\langle m_\nu \rangle = (0.05 - 0.84) \text{ eV}$ (3)

The result (2) and (3) determines the neutrino mass scenario to be degenerate ^{10,15}. The common mass eigenvalue follows then to be

$$m_{com} = (0.05 - 3.2) \text{ eV} \text{ (95\%)} \quad (4)$$

If we allow for other mechanisms (see ^{12,13,14,11}, the value given in eq. (2),(3) has to be considered as an upper limit. In that case very stringent limits arise for many other fields of beyond standard model physics. To give an example, it has been discussed recently ⁵⁶ that $0\nu\beta\beta$ decay by R-parity violating SUSY experimentally may not be excluded, although this would require making R-parity violating couplings generation dependent.

We show, in section III that indirect support for the observed evidence for neutrinoless double beta decay evidence comes from analysis of other Ge double beta experiments (though they are by far less sensitive, they yield independent information on the background in the region of the expected signal).

We discuss in sections IV and V some statistical features, about which still wrong ideas are around, as well as background simulations with the program GEANT4, which disprove some recent criticism.

In section VI we give a short discussion, stressing that the evidence for neutrinoless double beta decay ^{1,2,3,4,5} has been supported by various recent experimental results from other fields of research (see Table 1). It is consistent with recent results from cosmic microwave background experiments ^{63,64,66}. The precision of WMAP even allows to rule out some old-fashioned nuclear double beta decay matrix elements (see ⁶⁵).

Table 1. Recent support of the neutrino mass deduced from $0\nu\beta\beta$ decay ^{1,2,3,5} by other experiments, and by theoretical work.

Experiment	References	m_ν (degenerate ν 's)(eV)
$0\nu\beta\beta$	^{1,2,3,5}	0.05 - 3.2
WMAP	^{64,66}	< 0.23 , or 0.33 , or 0.50
CMB	⁶³	< 0.7
Z- burst	^{54,62}	0.08 - 1.3
g-2	⁵⁵	> 0.2
Tritium	³⁹	$< 2.2 - 2.8$
ν oscillation	^{58,59}	> 0.03
Theory (A_4 -symmetry)	⁶⁰	> 0.2
Theory (identical quark and ν mixing at GUT scale)	⁶¹	> 0.1

It has been shown to be consistent with the neutrino masses required for the Z-burst scenarios of high-energy cosmic rays ^{62,54}. It is consistent with a (g-2)

deviating from the standard model expectation⁵⁵. It is consistent also with the limit from the tritium decay experiments³⁹ but the allowed 95% confidence range extends down to a range which cannot be covered by future tritium experiments. It is further strongly supported by recent theoretical work^{60,61}.

Cosmological experiments like WMAP are now on the level that they can seriously contribute to terrestrial research. The fact that WMAP and less strictly also the tritium experiments cut away the upper part of the allowed range for the degenerate neutrino mass eq. (4) could indicate that the neutrino mass eigenvalues have the same CP parity¹⁶.

Finally we briefly comment about the possible future of the field of double beta decay, and present first results from GENIUS-TF which has come into operation on May 5, 2003 in Gran Sasso with first in world 10 kg of naked Germanium detectors in liquid nitrogen^{43,47,44}.

2. Evidence for the neutrinoless decay mode

The status of present double beta experiments is shown in Fig. 1 and is extensively discussed in¹⁴. The HEIDELBERG-MOSCOW experiment using the largest source strength of 11 kg of enriched ⁷⁶Ge (enrichment 86%) in form of five HP Ge-detectors is running since August 1990 in the Gran-Sasso underground laboratory^{14,5,6,2,41,37}.

The data taken in the period August 1990 - May 2000 (54.9813 kg y, or 723.44 mol-years) are shown in Fig. 2 in the section around the $Q_{\beta\beta}$ value of 2039.006 keV²⁵. Fig. 2 is identical with Fig. 1 in¹, except that we show here

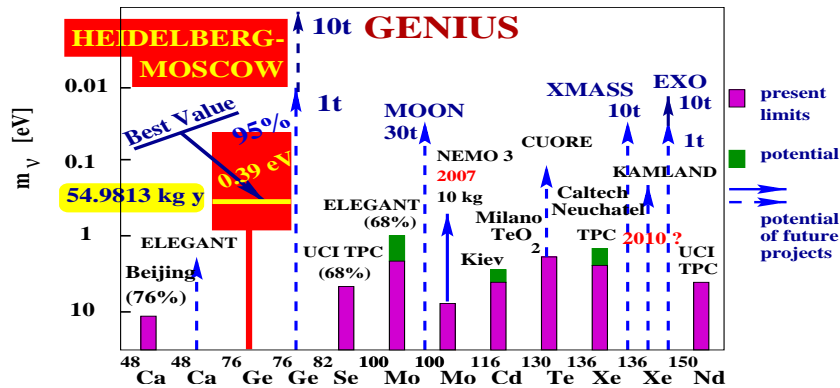


Figure 1. Present sensitivity, and expectation for the future, of the most promising $\beta\beta$ experiments. Given are limits for $\langle m \rangle$, except for the HEIDELBERG-MOSCOW experiment where the recently observed value is given (95% c.l. range and best value). Framed parts of the bars: present status; not framed parts: future expectation for running experiments; solid and dashed lines: experiments under construction or proposed, respectively. For references see^{14,2,5,52,50}.

the original energy binning of the data of 0.36 keV. These data have been analysed^{1,2,4,5} with various statistical methods, with the Maximum Likelihood Method and in particular also with the Bayesian method (see, e.g.⁵).

Our peak search procedure (for details see^{2,4,5}) reproduces (see^{1,2,4,5}) γ -lines at the positions of known weak lines²³ from the decay of ^{214}Bi at 2010.7, 2016.7, 2021.8 and 2052.9 keV. In addition, a line centered at 2039 keV shows up (see Fig. 3). This is compatible with the Q-value²⁵ of the double beta decay process. The Bayesian analysis yields, when analysing a $\pm 5\sigma$ range around $Q_{\beta\beta}$ (which is the usual procedure when searching for resonances in high-energy physics) a confidence level (i.e. the probability K) for a line to exist at 2039.0 keV of 96.5 % c.l. (2.1σ) (see Fig. 3). We repeated the analysis for the same data, but except detector 4, which had no muon shield and a slightly worse energy resolution (46.502 kg y). The probability we find for a line at 2039.0 keV in this

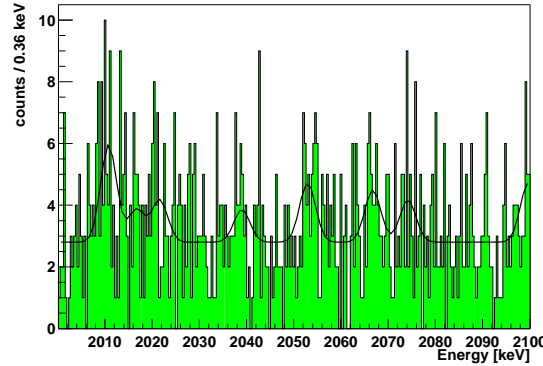


Figure 2. The spectrum taken with the ^{76}Ge detectors Nr. 1,2,3,4,5 over the period August 1990 - May 2000 (54.9813 kg y) in the original 0.36 keV binning, in the energy range 2000 - 2100 keV. Simultaneous fit of the ^{214}Bi lines and the two high-energy lines yield a probability for a line at 2039.0 keV of 91%.

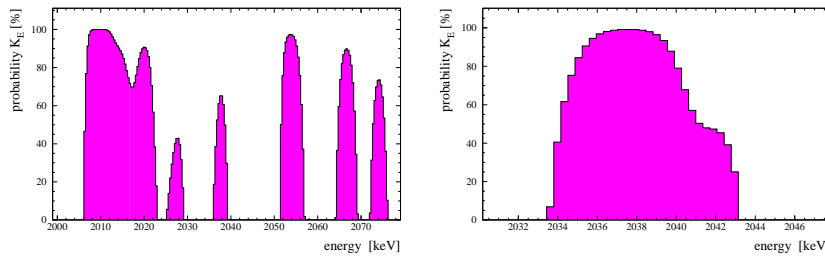


Figure 3. Left: Probability K that a line exists at a given energy in the range of 2000-2080 keV derived via Bayesian inference from the spectrum shown in Fig. 2. Right: Result of a Bayesian scan for lines as in the left part of this figure, but in an energy range of $\pm 5\sigma$ around $Q_{\beta\beta}$.

case is 97.4% (2.2σ)^{1,2,5}. Fitting a wide range of the spectrum yields a line at 2039 keV at 91% c.l. (see Fig.2).

We also applied the Feldman-Cousins method²¹. This method (which does not use the information that the line is Gaussian) finds a line at 2039 keV on a confidence level of 3.1σ (99.8% c.l.).

In addition to the line at 2039 keV we find candidates for lines at energies beyond 2060 keV and around 2030 keV, which at present cannot be attributed. This is a task of nuclear spectroscopy.

Important further information can be obtained from the *time structures* of the individual events. Double beta events should behave as single site events i.e. clearly different from a multiple scattered γ -event. It is possible to differentiate between these different types of events by pulse shape analysis. We have developed three methods of pulse shape analysis^{17,18,19} during the last seven years, one of which has been patented and therefore only published recently.

Installation of Pulse Shape Analysis (PSA) has been performed in 1995 for the four large detectors. Detector Nr.5 runs since February 1995, detectors 2,3,4 since November 1995 with PSA. The measuring time with PSA from November 1995 until May 2000 is 36.532 kg years, for detectors 2,3,5 it is 28.053 kg y.

In the SSE spectrum obtained under the restriction that the signal simultaneously fulfills the criteria of *all three* methods for a single site event, we find again indication of a line at 2039.0 keV (see^{1,2,5}).

With proper normalization concerning the running times (kg y) of the full and the SSE spectra, we see that almost the full signal remains after the single site cut (best value), while the ^{214}Bi lines (best values) are considerably reduced. We have used a ^{238}Th source to test the PSA method. We find the reduction of the 2103 keV and 2614 keV ^{228}Th lines (known to be multiple site or mainly multiple site), relative to the 1592 keV ^{228}Th line (known to be single site), shown in Fig. 4. This proves that the PSA method works efficiently. Essentially the same reduction as for the Th lines at 2103 and 2614 keV and for the weak Bi lines is found for the strong ^{214}Bi lines (e.g. at 609.6 and 1763.9 keV (Fig. 4)). The possibility, that the single site signal is the double escape line corresponding to a (much more intense!) full energy peak of a γ -line, at $2039+1022=3061$ keV is excluded from the high-energy part of our spectrum (see⁴).

3. Support of Evidence From Other Ge-Experiments and From Recent Measurements With a ^{214}Bi Source

It has been mentioned in Section II, that by the peak search procedure developed^{2,5} on basis of the Bayes and Maximum Likelihood Methods, exploiting as important input parameters the experimental knowledge on the shape and width of

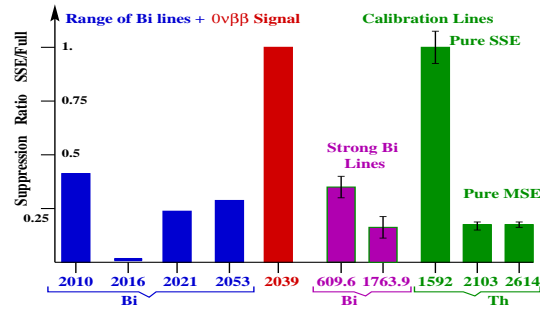


Figure 4. Relative suppression ratios: Remaining intensity after pulse shape analysis compared to the intensity in the full spectrum. Right: Result of a calibration measurement with a Th source - ratio of the intensities of the 1592 keV line (double escape peak, known to be 100% SSE), set to 1. The intensities of the 2203 keV line (single escape peak, known to be 100% MSE) are strongly reduced (error bars are $\pm 1\sigma$). The same order of reduction is found for the strong Bi lines occurring in our spectrum - shown in this figure are the lines at 609.4 and 1763.9 keV. Left: The lines in the range of weak statistics around the line at 2039 keV (shown are ratios of best fit values). The Bi lines are reduced compared to the line at 2039 keV (set to 1), as to the 1592 keV SSE Th line.

lines in the spectrum, weak lines of ^{214}Bi have been identified at the energies of 2010.78, 2016.7, 2021.6 and 2052.94 keV ^{1,2,5,7}. Fig. 3 shows the probability that there is a line of correct width and of Gaussian shape at a given energy, assuming all the rest of the spectrum as flat background (which is a highly conservative assumption).

The intensities of these ^{214}Bi lines have been shown to be consistent with other, strong Bi lines in the measured spectrum according to the branching ratios given in the Table of Isotopes ²³, and to Monte Carlo simulation of the experimental setup ⁵. Note that the 2016 keV line, as an E0 transition, can be seen only by coincident summing of the two successive lines $E = 1407.98$ keV and $E = 609.316$ keV. Its observation proves that the ^{238}U impurity from which it is originating, is located in the Cu cap of the detectors. Recent measurements of the spectrum of a ^{214}Bi source as function of distance source-detector confirm this interpretation ²⁶.

Premature estimates of the Bi intensities given in Aalseth et.al, hep-ex/0202018 and Feruglio et al., Nucl. Phys. B 637 (2002), 345, thus are incorrect, because this long-known spectroscopic effect of true coincident summing ²⁴ has not been taken into account, and also no simulation of the setup has been performed (for details see ^{5,3}).

These ^{214}Bi lines occur also in other investigations of double beta decay of Ge - and - even more important - also the additional structures in Fig. 2, which cannot be attributed at present, are seen in these other investigations.

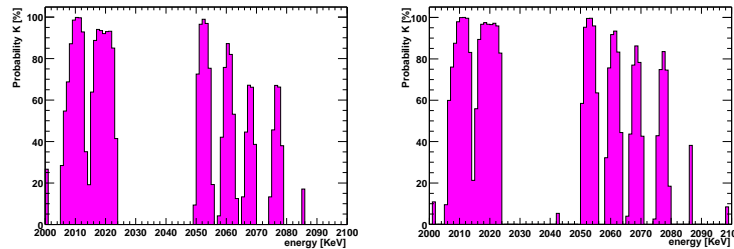


Figure 5. Result of the peak-search procedure performed for the UCBS/LBL spectrum ²⁹ (left: Maximum Likelihood method, right: Bayes method). On the y axis the probability of having a line at the corresponding energy in the spectrum is shown.

There are three other Ge experiments which have looked for double beta decay of ^{76}Ge . First there is the experiment by Caldwell et al. ²⁹, using natural Germanium detectors (7.8% abundance of ^{76}Ge , compared to 86% in the HEIDELBERG-MOSCOW experiment). This was the most sensitive *natural* Ge experiment. With their background a factor of 9 higher than in the HEIDELBERG-MOSCOW experiment and their measuring time of 22.6 kg years, they had a statistics of the background by a factor of almost four larger than in the HEIDELBERG-MOSCOW experiment. This gives useful information on the composition of the background.

Applying the same method of peak search as used in Fig. 3, yields indications for peaks essentially at the same energies as in Fig. 3 (see Fig. 5). This shows that these peaks are not fluctuations. In particular it sees the 2010.78, 2016.7, 2021.6 and 2052.94 keV ^{214}Bi lines, but also the unattributed lines at higher energies. It finds, however, no line at 2039 keV. This is consistent with the expectation from the rate found in the HEIDELBERG-MOSCOW experiment. About 16 observed events in the latter correspond to 0.6 expected events in the Caldwell experiment, because of the use of non-enriched material and the shorter measuring time. Fit of the Caldwell spectrum allowing for the ^{214}Bi lines and a 2039 keV line yields 0.4 events for the latter (see ⁵).

The first experiment using enriched (but not high-purity) Germanium 76 detectors was that of Kirpichnikov and coworkers ³⁰. These authors show only the energy range between 2020 and 2064 keV of their measured spectrum. The peak search procedure finds also here indications of lines around 2028 keV and 2052 keV (see Fig. 6), but not any indication of a line at 2039 keV. This is consistent with the expectation, because for their low statistics of 2.95 kg y they would expect here (according to HEIDELBERG-MOSCOW) 0.9 counts.

Another experiment (IGEX) used between 6 and 8.8 kg of enriched ^{76}Ge , but

collected since beginning of the experiment in the early nineties till shutdown in 1999 only 8.8 kg years of statistics ⁴⁹. The authors of ⁴⁹ unfortunately show only the range 2020 to 2060 keV of their measured spectrum in detail. Fig. 6 shows the result of our peak scanning of this range. Clear indications are seen for the Bi lines

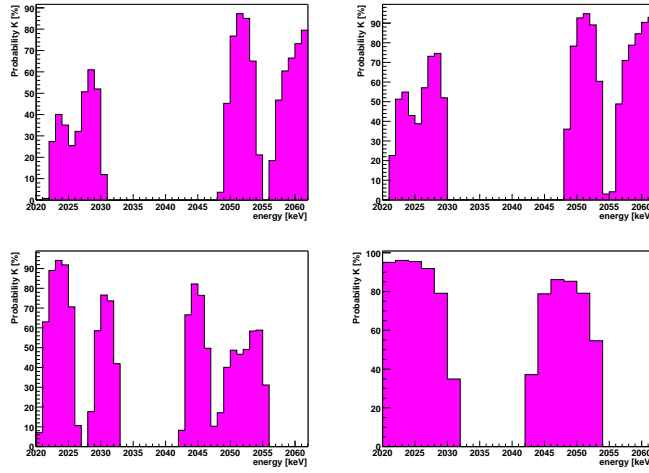


Figure 6. Result of the peak-search procedure performed for the ITEP/YePI spectrum ³⁰ (upper parts), and for the IGEX spectrum ⁴⁹ (lower parts). Left: Maximum Likelihood method, right: Bayes method. On the y axis the probability of having a line at the corresponding energy in the spectrum is shown.

at 2021 and 2052 keV, but also of the unidentified structure around 2030 keV. Because of the conservative assumption on the background treatment in the scanning procedure (see above) there is no chance to see a signal at 2039 keV because of the 'hole' in the background of that spectrum (see Fig. 1 in ⁴⁹). With some good will one might see, however, an indication of 3 events here, consistent with the expectation of the HEIDELBERG-MOSCOW experiment of 2.6 counts.

4. Statistical Features: Sensitivity of Peak Search, Analysis Window

At this point it may be useful to demonstrate the potential of the used peak search procedure. Fig. 7 shows a spectrum with Poisson-generated background of 4 events per channel and a Gaussian line with width (standard deviation) of 4 channels centered at channel 50, with intensity of 10 (left) and 100 (right) events, respectively. Fig. 8, shows the result of the analysis of spectra of different line intensity with the Bayes method (here Bayes 1-4 correspond to different choice of the prior distribution: (1) $\mu(\eta) = 1$ (flat), (2) $\mu(\eta) = 1/\eta$, (3) $\mu(\eta) = 1/\sqrt{\eta}$, (4) Jeffrey's prior) and the Maximum Likelihood Method. For each prior 1000 spectra have been generated with equal background and equal line intensity using random number generators available at CERN ²⁰. The average values of the best values agree (see Fig. 8) very well with the known intensities also for very low count rates (as in Fig. 7, left).

In Fig. 9 we show two simulations of a Gaussian line of 15 events, centered at channel 50, again with width (standard deviation) of 4 channels, on a Poisson-distributed background with 0.5 events/channel. The figure gives an indication of the possible degree of deviation of the energy of the peak maximum from the transition energy, on the level of statistics collected in experiments like the HEIDELBERG-MOSCOW experiment (here one channel corresponds to 0.36 keV). This should be considered when comparing Figs. 3, 5,6.

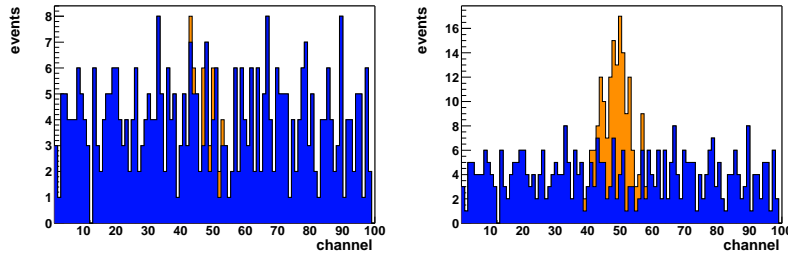


Figure 7. Example of a random-generated spectrum with a Poisson distributed background with 4.0 events per channel and a Gaussian line centered in channel 50 (line-width corresponds to a standard-deviation of $\sigma = 4.0$ channels). The left picture shows a spectrum with a line-intensity of 10 events, the right spectrum a spectrum with a line-intensity of 100 events. The background is shown dark, the events of the line bright (from ^{28,8}).

The influence of the choice of the energy range of the analysis around $Q_{\beta\beta}$ has been thoroughly discussed in ^{2,5}. Since erroneous ideas about this point are still around, let us remind of the analysis given in ^{2,5,8} which showed that a reliable result is obtained for a range of analysis of not smaller than 35 channels (i.e. ± 18 channels) - one channel corresponding to 0.36 keV in the HEIDELBERG-MOSCOW experiment. This is an important result, since it is of course important to keep the range of analysis as small as possible, to avoid to include lines in the vicinity of the weak signal into the background. This unavoidably occurs when e.g. proceeding as suggested in F. Feruglio et al., hep-ph/0201291 and Nucl. Phys. B 637 (2002) 345-377, Aalseth et. al., hep-ex/0202018 and Mod. Phys. Lett. A 17 (2002) 1475, Yu.G. Zdesenko et. al., Phys. Lett. B 546 (2002) 206. The arguments given in those papers are therefore incorrect. Also Kirpichnikov, who states ³⁰ that his analysis finds a 2039 keV signal in the HEIDELBERG-MOSCOW spectrum on a 4 sigma confidence level (as we also see it, when using the Feldman-Cousins method ²⁸), makes this mistake when analyzing the pulse-shape spectrum.

5. Simulation with GEANT4

Finally the background around $Q_{\beta\beta}$ will be discussed from the side of simulation. A very careful new simulation of the different components of radioactive background in the HEIDELBERG-MOSCOW experiment has been performed recently by a new Monte Carlo program based on GEANT4^{27,8}. This simulation uses a new event generator for simulation of radioactive decays basing on ENSDF-data and describes the decay of arbitrary radioactive isotopes including alpha, beta and gamma emission as well as conversion electrons and X-ray emission. Also included in the simulation is the influence of neutrons in the energy range from thermal to high energies up to 100 MeV on the measured spectrum. Elastic and inelastic reactions, and capture have been taken into account, and the corresponding production of radioactive isotopes in the setup. The neutron fluxes and energy distributions were taken from published measurements performed in the Gran Sasso.

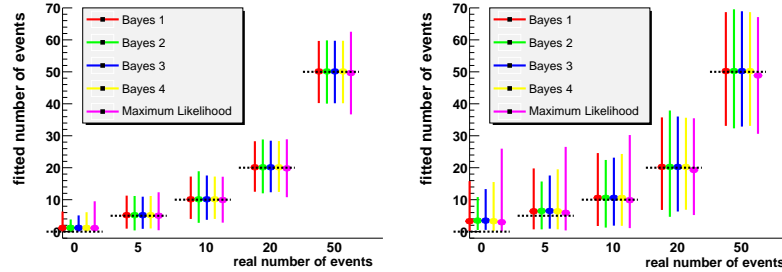


Figure 8. Results of analysis of random-number generated spectra, using Bayes and Maximum Likelihood method (the first one with different prior distributions). For each number of events in the simulated line, shown on the x-axis, 1000 random generated spectra were evaluated with the five given methods. The analysis on the left side was performed with an Poisson distributed background of 0.5 events per channel, the background for the spectra on the right side was 4.0 events per channel. Each vertical line shows the mean value of the calculated best values (thick points) with the 1σ error area. The mean values are in good agreement with the expected values (horizontal black dashed lines) (from^{28,8}).

Also simulated was the cosmic muon flux measured in the Gran Sasso, on the measured spectrum. To give a feeling for the quality of the simulation, Fig. 10 shows the simulated and the measured spectra for a ^{228}Th source spectrum for as example one of our five detectors. The agreement is excellent.

The simulation of the background of the experiment reproduces a ll observed lines in the energy range between threshold (around 100 keV) and 2020 keV^{27,8}.

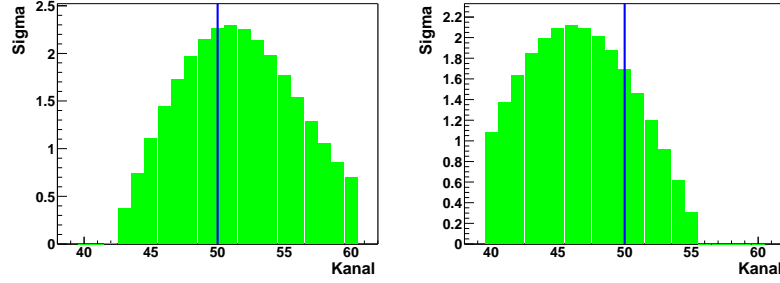


Figure 9. Two spectra with a Poisson-distributed background and a Gaussian line with 15 events centered in channel 50 (with a width (standard-deviation) of 4.0 channels) created with different random numbers. Shown is the result of the peak-scanning of the spectra. In the left picture the maximum of the probability corresponds well with the expected value (black line) whereas in the right picture a larger deviation is found. When a channel corresponds to 0.36 keV the deviation in the right picture is ~ 1.44 keV (from ^{28,8}).

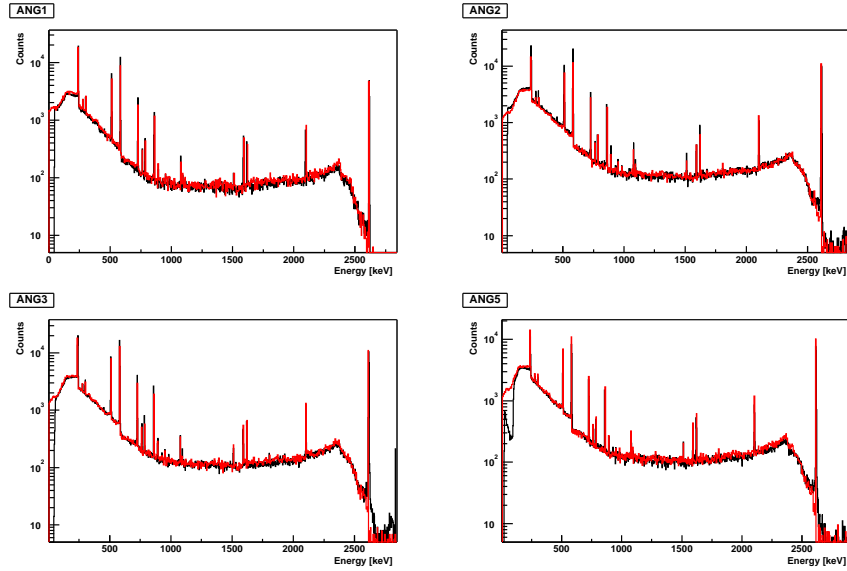


Figure 10. Comparison of the measured data (black line, November 1995 to April 2002) and simulated spectrum (red line) for the detectors Nrs. 1,2,3 and 5 for a ²³²Th source spectrum. The agreement of simulation and measurement is excellent (from ^{27,8}).

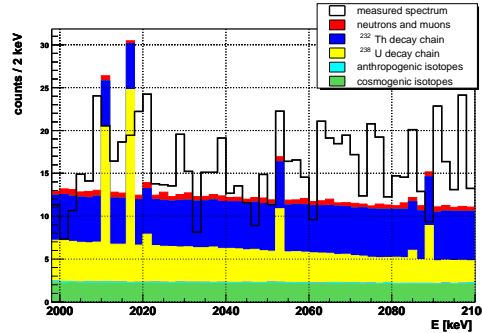


Figure 11. Simulated background of the HEIDELBERG-MOSCOW experiment in the energy range from 2000 to 2100 keV with all known background components. The black histogram line corresponds to the measured data from 20.11.1995 to 16.4.2002 (49.59 kg y) (from ^{27,8}).

Fig. 11 shows the simulated background in the range 2000-2100keV with all known background components. The black histogram corresponds to the measured data in the period 20.11.1995 - 16.4.2002 (49.59 kg y).

The background around $Q_{\beta\beta}$ is according to the simulations flat, the only expected lines come from ²¹⁴Bi (from the ²³⁸U natural decay chain) at 2010.89, 2016.7, 2021.6, 2052.94, 2085.1 and 2089.7 keV. Lines from cosmogenically produced ⁵⁶Co (at 2034.76keV and 2041.16keV), half-life 77.3 days, are not expected since the first 200 days of measurement of each detector are not used in the data analysis. Also the potential contribution from decays of ⁷⁷Ge, ⁶⁶Ga, or ²²⁸Ac, should not lead to signals visible in our measured spectrum near the signal at $Q_{\beta\beta}$. For details we refer to ⁸.

6. Proofs and disproofs

The result described in section 2.1 has been questioned in some papers (Aalseth et al, hep-ex/0202018, and in Mod. Phys. Lett. A 17 92002) 1475-1478; Feruglio et al., Nucl. Phys. B 637 (2002) 345; Zdesenko et al., Phys. Lett. B 546 (2002) 206). We think that we have shown in a convincing way that these claims against our results are incorrect in various ways. In particular the estimates of the intensities of the ²¹⁴Bi lines in the first two papers do not take into account the effect of true coincidence summing, which can lead to drastic underestimation of the intensities. A correct estimate would also require a Monte Carlo simulation of our setup, which has not been performed in the above papers. All of these papers, when discussing the choice of the width of the search window, seem to ignore the results

of the statistical simulations we published in ^{2,3,4,5}. For details we refer to ^{2,3,4,5,7}.

7. Discussion of results

7.1. Half-life and effective neutrino mass

We emphasize that we find in all analyses of our spectra a line at the value of $Q_{\beta\beta}$. We have shown that the signal at $Q_{\beta\beta}$ does not originate from a background γ -line. On this basis we translate the observed number of events into half-lives for the neutrinoless double beta decay. We give in Table 2 conservatively the values obtained with the Bayesian method and not those obtained with the Feldman-Cousins method. Also given in Table 2 are the effective neutrino masses $\langle m \rangle$ deduced using the matrix elements of ²².

Table 2. Half-life for the neutrinoless decay mode and deduced effective neutrino mass from the HEIDELBERG-MOSCOW experiment.

$kg\ y$	Detectors	$T_{1/2}^{0\nu}\ y$	$\langle m \rangle\ eV$	C.L.
54.9813	1,2,3,4,5	$(0.80 - 35.07) \times 10^{25}$ $(1.04 - 3.46) \times 10^{25}$ 1.61×10^{25}	$(0.08 - 0.54)$ $(0.26 - 0.47)$ 0.38	95% <i>c.l.</i> 68% <i>c.l.</i> Best Value
46.502	1,2,3,5	$(0.75 - 18.33) \times 10^{25}$ $(0.98 - 3.05) \times 10^{25}$ 1.50×10^{25}	$(0.11 - 0.56)$ $(0.28 - 0.49)$ 0.39	95% <i>c.l.</i> 68% <i>c.l.</i> Best Value
28.053	2,3,5 SSE	$(0.88 - 22.38) \times 10^{25}$ $(1.07 - 3.69) \times 10^{25}$ 1.61×10^{25}	$(0.10 - 0.51)$ $(0.25 - 0.47)$ 0.38	90% <i>c.l.</i> 68% <i>c.l.</i> Best Value

We derive from the data taken with 46.502 kg y the half-life $T_{1/2}^{0\nu} = (0.8 - 18.3) \times 10^{25}\ y$ (95% c.l.). The analysis of the other data sets, shown in Table 2 confirm this result. Of particular importance is that we see the $0\nu\beta\beta$ signal in the single site spectrum.

The result obtained is consistent with all other double beta experiments - which still reach in general by far less sensitivity. The most sensitive experiments following the HEIDELBERG-MOSCOW experiment are the geochemical ¹²⁸Te experiment with $T_{1/2}^{0\nu} > 2(7.7) \times 10^{24}\ y$ (68% c.l.), ³¹ the ¹³⁶Xe experiment by the DAMA group with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}\ y$ (90% c.l.), a second enriched ⁷⁶Ge experiment with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}\ y$ ³⁰ and a ^{nat}Ge experiment with $T_{1/2}^{0\nu} > 1 \times 10^{24}\ y$ ²⁹. Other experiments are already about a factor of 100 less sensitive concerning the $0\nu\beta\beta$ half-life: the Gotthard TPC experiment with ¹³⁶Xe yields ³² $T_{1/2}^{0\nu} > 4.4 \times 10^{23}\ y$ (90% c.l.) and the Milano Mibeta cryodetector experiment $T_{1/2}^{0\nu} > 1.44 \times 10^{23}\ y$ (90% c.l.).

Another experiment ⁴⁹ with enriched ⁷⁶Ge, which has stopped operation in

1999 after reaching a significance of 8.8 kg y, yields (if one believes their method of 'visual inspection' in their data analysis), in a conservative analysis, a limit of about $T_{1/2}^{0\nu} > 5 \times 10^{24}$ y (90% c.l.). The ^{128}Te geochemical experiment yields $\langle m_\nu \rangle < 1.1$ eV (68 % c.l.)³¹, the DAMA ^{136}Xe experiment $\langle m_\nu \rangle < (1.1 - 2.9)$ eV and the ^{130}Te cryogenic experiment yields $\langle m_\nu \rangle < 1.8$ eV.

Concluding we obtain, with $> 95\%$ probability, first evidence for the neutrinoless double beta decay mode. As a consequence, at this confidence level, lepton number is not conserved. Further the neutrino is a Majorana particle. If the $0\nu\beta\beta$ amplitude is dominated by exchange of a massive neutrino the effective mass $\langle m \rangle$ is deduced (using the matrix elements of²²) to be $\langle m \rangle = (0.11 - 0.56)$ eV (95% c.l.), with best value of 0.39 eV. Allowing conservatively for an uncertainty of the nuclear matrix elements of $\pm 50\%$ (for detailed discussions of the status of nuclear matrix elements we refer to^{14,5} and references therein) this range may widen to $\langle m \rangle = (0.05 - 0.84)$ eV (95% c.l.).

Assuming other mechanisms to dominate the $0\nu\beta\beta$ decay amplitude, the result allows to set stringent limits on parameters of SUSY models, leptoquarks, compositeness, masses of heavy neutrinos, the right-handed W boson and possible violation of Lorentz invariance and equivalence principle in the neutrino sector. For a discussion and for references we refer to^{14,33,36,13,50,11}.

With the limit deduced for the effective neutrino mass, the HEIDELBERG-MOSCOW experiment excludes several of the neutrino mass scenarios allowed from present neutrino oscillation experiments (see Fig. 12) - allowing only for degenerate, and marginally still for inverse hierarchy mass scenarios^{10,15}.

The evidence for neutrinoless double beta decay has been supported by various recent experimental and theoretical results (see Table 1). Assuming the degenerate scenarios to be realized in nature we fix - according to the formulae derived in⁹ - the common mass eigenvalue of the degenerate neutrinos to $m = (0.05 - 3.4)$ eV. Part of the upper range is already excluded by tritium experiments, which give a limit of $m < 2.2-2.8$ eV (95% c.l.)³⁹. The full range can only partly (down to ~ 0.5 eV) be checked by future tritium decay experiments, but could be checked by some future $\beta\beta$ experiments (see next section). The deduced best value for the mass is consistent with expectations from experimental $\mu \rightarrow e\gamma$ branching limits in models assuming the generating mechanism for the neutrino mass to be also responsible for the recent indication for an anomalous magnetic moment of the muon⁵⁵. It lies in a range of interest also for Z-burst models recently discussed as explanation for super-high energy cosmic ray events beyond the GKZ-cut-off^{54,62} and requiring neutrino masses in the range (0.08 - 1.3) eV. A recent model with underlying A_4 symmetry for the neutrino mixing matrix also leads to degenerate neutrino masses > 0.2 eV, consistent with the present result from $0\nu\beta\beta$ decay

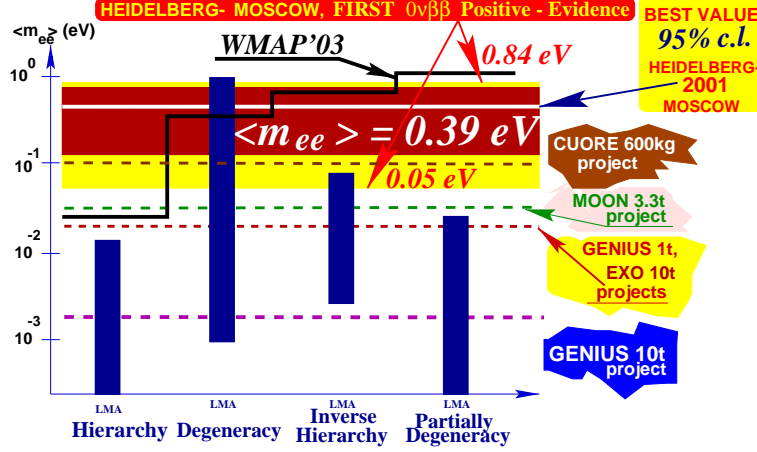


Figure 12. The impact of the evidence obtained for neutrinoless double beta decay (best value of the effective neutrino mass $\langle m \rangle = 0.39$ eV, 95% confidence range (0.05 - 0.84) eV - allowing already for an uncertainty of the nuclear matrix element of a factor of $\pm 50\%$) on possible neutrino mass schemes. The bars denote allowed ranges of $\langle m \rangle$ in different neutrino mass scenarios, still allowed by neutrino oscillation experiments (see ^{10,15}). Hierarchical models are excluded by the new $0\nu\beta\beta$ decay result. Also shown is the exclusion line from WMAP, plotted for $\sum m_\nu < 1.0$ eV ⁶⁶. WMAP does not rule out any of the neutrino mass schemes. Further shown are the expected sensitivities for the future potential double beta experiments CUORE, MOON, EXO and the 1 ton and 10 ton project of GENIUS ^{14,13,51,35} (from ¹⁵).

^{57,60}. The result is further consistent with the theoretical paper of ⁶¹. Starting with the hypothesis that quark and lepton mixing are identical at or near the GUT scale, Mohapatra et al. ⁶¹ show that the large solar and atmospheric neutrino mixing angles can be understood purely as result of renormalization group evolution, if neutrino masses are quasi-degenerate (with same CP parity). The common Majorana neutrino mass then must be, in this model, larger than 0.1 eV.

For WMAP a limit on the total neutrino masses of

$$m_s = \sum m_i < 0.69 \text{ eV} \quad \text{at } 95\% \text{ c.l.}, \quad (5)$$

is given by the analysis of ref. ⁶⁴. It has been shown, however, that this limit may not be very realistic. Another analysis shows that this limit on the total mass should be ⁶⁶

$$m_s = \sum m_i < 1.0 \text{ eV} \quad \text{at } 95\% \text{ c.l.} \quad (6)$$

The latter analysis also shows, that four generations of neutrinos are still allowed and in the case of four generations the limit on the total mass is increased to 1.38 eV. If there is a fourth neutrino with very small mass, then the limit on the total

mass of the three neutrinos is even further weakened and there is essentially no constraint on the neutrino masses. In our Fig. 12 we show the contour line for WMAP assuming $\sum m_i < 1.0$ eV.

Comparison of the WMAP results with the effective mass from double beta decay rules out completely (see ⁶⁵) a 15 years old old-fashioned nuclear matrix element of double beta decay, used in a recent analysis of WMAP ⁶⁷. In that calculation of the nuclear matrix element there was not included a realistic nucleon-nucleon interaction, which has been included by all other calculations of the nuclear matrix elements over the last 15 years.

As mentioned in section 1 the results from double beta decay and WMAP *together* may indicate ¹⁶ that the neutrino mass eigenvalues have indeed the same CP parity, as required by the model of ⁶¹.

The range of $\langle m \rangle$ fixed in this work is, already now, in the range to be explored by the satellite experiments MAP and PLANCK ^{9,64,66}. The limitations of the information from WMAP are seen in Fig. 12, thus results of PLANCK are eagerly awaited.

The neutrino mass deduced leads to $0.002 \geq \Omega_\nu h^2 \leq 0.1$ and thus may allow neutrinos to still play an important role as hot dark matter in the Universe ⁴².

8. Future of $\beta\beta$ experiments - GENIUS and other proposals

With the HEIDELBERG-MOSCOW experiment, the era of the small smart experiments is over. New approaches and considerably enlarged experiments (as discussed, e.g. in ^{12,33,14,36,51,35,38,42}) will be required in future to fix the neutrino mass with higher accuracy.

Since it was realized in the HEIDELBERG-MOSCOW experiment, that the remaining small background is coming from the material close to the detector (holder, copper cap, ...), elimination of *any* material close to the detector will be decisive. Experiments which do not take this into account, like, e.g. CUORE and MAJORANA will allow at best only rather limited steps in sensitivity. Furthermore there is the problem in cryodetectors that they cannot differentiate between a β and a γ signal, as this is possible in Ge experiments.

Another crucial point is the energy resolution, which can be optimized *only* in experiments using Germanium detectors or bolometers. It will be difficult to probe evidence for this rare decay mode in experiments, which have to work - as result of their limited resolution - with energy windows around $Q_{\beta\beta}$ of several hundreds of keV, such as NEMO III, EXO, CAMEO.

Another important point is the efficiency of a detector for detection of a $\beta\beta$ signal. For example, with 14% efficiency a potential future 100 kg ⁸²Se NEMO experiment would be, because of its low efficiency, equivalent only to a 10 kg

experiment (not talking about the energy resolution).

In the first proposal for a third generation double beta experiment, the GENIUS proposal^{33,12,34,36,51,35}, the idea is to use 'naked' Germanium detectors in a huge tank of liquid nitrogen. It seems to be at present the *only* proposal, which can fulfill *both* requirements mentioned above - to increase the detector mass and simultaneously reduce the background drastically. GENIUS would - with only 100 kg of enriched ^{76}Ge - increase the confidence level of the present pulse shape discriminated $0\nu\beta\beta$ signal to 4σ within one year, and to 7σ within three years of measurement (a confirmation on a 4σ level by the MAJORANA project would need according to our estimate at least ~ 230 years, the CUORE project might need - ignoring for the moment the problem of identification of the signal as a $\beta\beta$ signal - 3700 years). With ten tons of enriched ^{76}Ge GENIUS should be capable to investigate also whether the neutrino mass mechanism or another mechanism (see, e.g.¹⁴) is dominating the $0\nu\beta\beta$ decay amplitude.

9. GENIUS-TF

As a first step of GENIUS, a small test facility, GENIUS-TF, is under installation in the Gran Sasso Underground Laboratory^{47,45} since March 2001. With up to 40 kg of natural Ge detectors operated in liquid nitrogen, GENIUS-TF could test the DAMA seasonal modulation signature for dark matter⁴⁴. No other experiment running like, CDMS, IGEX, etc., or projected at present, will have this potential⁴². Up to summer 2001, already six 2.5 kg Germanium detectors with an extreme low-level threshold of ~ 500 eV have been produced.

The idea of GENIUS-TF is to prove the feasibility of some key constructional features of GENIUS, such as detector holder systems, achievement of very low thresholds of specially designed Ge detectors, long term stability of the new detector concept, reduction of possible noise from bubbling nitrogen, etc.

After installation of the GENIUS-TF setup between halls A and B in Gran Sasso, opposite to the buildings of the HEIDELBERG-MOSCOW double beta decay experiment and of the DAMA experiment, the first four detectors have been installed in liquid nitrogen on May 5, 2003 and have started operation^{43,26} (Fig.13).

This is the first time ever, that this novel technique for extreme background reduction in search for rare decays is tested under realistic background conditions in an underground laboratory.

10. Conclusion

The status of present double beta decay search has been discussed, and recent evidence for a non-vanishing Majorana neutrino mass obtained by the



Figure 13. Left: The first four naked Ge detectors before installation into the GENIUS-TF setup. Right: Taking out the crystals from the transport dewars and fixing the electrical contacts in the clean room of the GENIUS-TF building - from left to right: Herbert Strecker, Hans Volker Klapdor-Kleingrothaus, Oleg Chkvorez.

HEIDELBERG-MOSCOW experiment has been presented. Additional support for this evidence has been presented by showing consistency of the result - for the signal, and for the background - with other double beta decay experiments using non-enriched or enriched Germanium detectors. In particular it has been shown that the lines seen in the vicinity of the signal (including those which at present cannot be attributed) are seen also in the other experiments. This is important for the correct treatment of the background. Furthermore, the sensitivity of the peak identification procedures has been demonstrated by extensive statistical simulations. It has been further shown by new extensive simulations of the expected background by GEANT4, that the background around $Q_{\beta\beta}$ should be flat, and that no known gamma line is expected at the energy of $Q_{\beta\beta}$. The 2039 keV signal is seen only in the HEIDELBERG-MOSCOW experiment, which has a *by far* larger statistics than all other double beta experiments.

The importance of this first evidence for violation of lepton number and of the Majorana nature of neutrinos is obvious. It requires beyond Standard Model Physics on one side, and may open a new era in space-time structure⁵³. It has been discussed that the Majorana nature of the neutrino tells us that spacetime does realize a construct that is central to construction of supersymmetric theories.

With the successful start of operation of GENIUS-TF with the first four naked Ge detectors in liquid nitrogen on May 5, 2003 in GRAN SASSO, which is described in^{44,43} a historical step has been achieved of a novel technique and into a new domain of background reduction in underground physics in the search for rare events.

Future projects to improve the present accuracy of the effective neutrino mass have been briefly discussed. The most sensitive of them and perhaps at the same time most realistic one, is the GENIUS project. GENIUS is the only of the new projects which simultaneously has a huge potential for cold dark matter search, and for real-time detection of low-energy neutrinos (see^{12,33,38,40,13,14,48,52,50}).

References

1. H.V. Klapdor-Kleingrothaus et al. *Mod. Phys. Lett. A* **16** (2001) 2409 - 2420.
2. H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina, *Part. and Nucl.* **110** (2002) 57.
3. H.V. Klapdor-Kleingrothaus, hep-ph/0205228, in Proc. of DARK2002, eds. by H.V. Klapdor-Kleingrothaus and R.D. Viollier, Springer (2002) 404.
4. H.V. Klapdor-Kleingrothaus, hep-ph/0302248, Proc. DARK2002, Springer (2002) 367.
5. H.V. Klapdor-Kleingrothaus, A. Dietz and I.V. Krivosheina, *Foundations of Physics* **31** (2002) 1181 and Corr., 2003: http://www.mpi-hd.mpg.de/non_acc/main_results.html.
6. H.V. Klapdor-Kleingrothaus et al., (HEIDELBERG-MOSCOW Col.), *Eur. Phys. J. A* **12** (2001) 147, Proc. DARK2000, ed. H.V. Klapdor-Kleingrothaus, Springer (2001) 520.
7. H.V. Klapdor-Kleingrothaus, hep-ph/0303217 and in Proc. of "Neutrinos and Implications for Phys. Beyond the SM", Stony Brook, 11-13 Oct. 2002.
8. H.V. Klapdor-Kleingrothaus et al., to be publ. in 2003.
9. H.V. Klapdor-Kleingrothaus, H. Päs, A. Yu. Smirnov, *Phys. Rev. D* **63** (2001) 073005.
10. H.V. Klapdor-Kleingrothaus and U. Sarkar, *Mod. Phys. Lett. A* **16** (2001) 2469.
11. H.V. Klapdor-Kleingrothaus and U. Sarkar, hep-ph/0302237.
12. H.V. Klapdor-Kleingrothaus, *Int. J. Mod. Phys. A* **13** (1998) 3953.
13. H.V. Klapdor-Kleingrothaus, *Springer Tracts in Modern Physics*, **163** (2000) 69 - 104, Springer-Verlag, Heidelberg, Germany (2000).
14. H.V. Klapdor-Kleingrothaus, "60 Years of Double Beta Decay - From Nuclear Physics to Beyond the Standard Model", *World Scientific, Singapore* (2001) 1281 p.
15. H.V. Klapdor-Kleingrothaus and U. Sarkar, hep-ph/0304032.
16. H.V. Klapdor-Kleingrothaus, to be publ. 2003, and Proc. BEYOND02, IOP, Bristol 2003.
17. J. Hellmig and H.V. Klapdor-Kleingrothaus, *NIM A* **455** (2000) 638-644.
18. J. Hellmig, F. Petry and H.V. Klapdor-Kleingrothaus, *Patent DE19721323A*.
19. B. Majorovits and H.V. Klapdor-Kleingrothaus, *Eur. Phys. J. A* **6** (1999) 463.
20. CERN number generators (see e.g. <http://root.cern.ch/root/html/TRandom.html>)
21. D.E. Groom et al., Particle Data Group, *Eur. Phys. J. C* **15** (2000) 1.
22. A. Staudt, K. Muto and H.V. Klapdor-Kleingrothaus, *Eur. Lett.* **13** (1990) 31.
23. R.B. Firestone and V.S. Shirley, Table of Isotopes, 8th Ed., *John Wiley & Sons*, N.Y. (1998).
24. G. Gilmore et al. "Practical Gamma-Ray Spectr.", Wiley and Sons (1995).
25. G. Douysset et al., *Phys. Rev. Lett.* **86** (2001) 4259 - 4262.
26. H.V. Klapdor-Kleingrothaus, O. Chkvorets, I.V. Krivosheina, C. Tomei, in press NIM'03.
27. Ch. Dörr, Diplomarbeit (2002), Univ. of Heidelberg, unpubl.
28. A. Dietz, Dissertation, University of Heidelberg, 2003.
29. D. Caldwell, *J. Phys. G* **17**, S137-S144 (1991).
30. I.V. Kirpichnikov et al. *Mod. Phys. Lett. A* **5** (1990) 1299 - 1306. Preprint ITEP, 1991, Moscow 91-91.
31. O. Manuel et al., in Proc. Intern. Conf. Nuclear Beta Decays and the Neutrino, eds. T. Kotani et al., World Scientific (1986) 71, *J. Phys. G: Nucl. Part. Phys.* **17** (1991) S221-S229; T. Bernatovicz et al. *Phys. Rev. Lett.* **69** (1992) 2341.
32. R. Lüscher et al., *Phys. Lett.* (1998) 407.
33. H.V. Klapdor-Kleingrothaus in Proc. of BEYOND'97, IOP Bristol (1998) 485-531.

34. H.V. Klapdor-Kleingrothaus, J. Hellmig and M. Hirsch, *J. Phys.* **G 24** (1998) 483 - 516.
35. H.V. Klapdor-Kleingrothaus et al. MPI-Report MPI-H-V26-1999, hep-ph/9910205, in Proc. of BEYOND'99, eds. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, *IOP Bristol* (2000) 915.
36. H.V. Klapdor-Kleingrothaus, in Proc. of NEUTRINO 98, Takayama, Japan, 4-9 Jun 1998, (eds) Y. Suzuki et al. *Nucl. Phys. Proc. Suppl.* **77** (1999) 357.
37. HEIDELBERG-MOSCOW Coll. (M. Günther et al.), *Phys.Rev.***D55**(1997)54.
38. H.V. Klapdor-Kleingrothaus, *Nucl. Phys.* **B 100** (2001) 309 - 313.
39. J. Bonn et al., *Nucl. Phys.* **B 91** (2001) 273 - 279.
40. V.A. Bednyakov and H.V. Klapdor-Kleingrothaus, *Phys. Rev.* **D 63** (2001) 095005.
41. H.V. Klapdor-Kleingrothaus, in Proc. eds.: D. Poenaru and S. Stoica, *World Scientific, Singapore* (2000) 123-129.
42. H.V. Klapdor-Kleingrothaus, *Int.J.Mod.Phys.***A17**(2002)3421, Proc. LP01, WS 2002.
43. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, in Proc. of BEYOND02, Oulu, Finland, June 2002, IOP 2003, ed. H.V. Klapdor-Kleingrothaus.
44. H. V. Klapdor-Kleingrothaus, et al., NIM 2003, in press.
45. T. Kihm, V. F. Bobrakov and H.V. Klapdor-Kleingrothaus *NIM* **A498** (2003) 334.
46. H.V. Klapdor-Kleingrothaus et al., Internal Report **MPI-H-V32-2000**.
47. H.V. Klapdor-Kleingrothaus et al., hep-ph/0103082, *NIM* **A 481** (2002) 149.
48. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, in Proc. of "Forum of Physics", Zacatecas, Mexico, 11-13 May, 2002, eds. D.V. Ahluwalia and M. Kirchbach.
49. C.E. Aalseth et al. (IGEX Collaboration), *Yad. Fiz.* **63, No 7** (2000) 1299 - 1302; *Phys. Rev.* **D 65** (2002) 092007.
50. H.V. Klapdor-Kleingrothaus, *Part. and Nucl., Lett.* iss. 1/2(2001), hep-ph/0102319.
51. H.V. Klapdor-Kleingrothaus, hep-ph/0103074 and in NOON 2000, W.S.(2001) 219.
52. H.V. Klapdor-Kleingrothaus, LowNu2, WS(2001)116, hep-ph/0104028.
53. D.V. Ahluwalia in Proc. of BEYOND02, IOP 2003, ed. H.V. Klapdor-Kleingrothaus; D.V. Ahluwalia, M. Kirchbach, *Phys. Lett.* **B 529** (2002) 124.
54. D. Fargion et al., in Proc. of DARK2000, *Springer*, (2001) 455, in Proc. of BEYOND02, IOP 2003, ed. H.V. Klapdor-Kleingrothaus.
55. E. Ma and M. Raidal, *Phys.Rev.Lett.*87(2001)011802; Erratum-ibid.87(2001)159901.
56. Y. Uehara, *Phys. Lett.* **B 537** (2002) 256-260 and hep-ph/0201277.
57. E. Ma in Proc. of BEYOND'02, Oulu, Finland, 2-7 Jun. 2002, IOP, Bristol, 2003, ed. H.V. Klapdor-Kleingrothaus.
58. KamLAND Coll., *Phys. Rev. Lett.* **90** (2003) 021802 and hep-ex/0212021.
59. G. L. Fogli et al., *Phys. Rev.* **D 67** (2003) 073002 and hep-ph/0212127.
60. K. S. Babu, E. Ma and J.W.F. Valle (2002) hep-ph/0206292.
61. R. N. Mohapatra, M. K. Parida and G. Rajasekaran, (2003) hep-ph/0301234.
62. Z. Fodor, S. D. Katz and A. Ringwald, *Phys. Rev. Lett.* **88** (2002) 171101; Z. Fodor et al., *JHEP* (2002) 0206:046, or hep-ph/0203198, and in Proc. of BEYOND'02, IOP, Bristol, 2003, ed. H V Klapdor-Kleingrothaus and hep-ph/0210123.
63. J. E. Ruhl et al., astro-ph/0212229.
64. D. N. Spergel et al., astro-ph/0302209.
65. A. Pierce and H. Murayama, hep-ph/0302131.
66. S. Hannestad, astro-ph/0303076.

67. P. Vogel in PDG (ed. K Hagiwara et al.) *Phys. Rev.* (2002) **D 66** 010001.